Construction Innovation 2006; **6**: 47–60

HyCon: virtual prototyping in hybrid concrete construction frame design

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Submitted 8 Februray 2005; **accepted** 25 October 2005

Abstract: Hybrid concrete construction is a technologically advanced approach to frame construction. It utilizes an optimal mix of structural materials; eg, *in situ* concrete with precast concrete and steelwork. The process of selecting an hybrid-optimized solution, however, often requires several factors to be considered, eg, 'hard' criteria such as time and cost, and 'soft' criteria such as safety and aesthetics (to be considered simultaneously) - the complexities of which can often be a core barrier to implementation. This paper introduces the concept of hybrid concrete construction and presents a virtual prototyping tool to assist the decision-making process. This model is able to import computer aided design information into a central database - the details of which are then layered with additional information; eg, hard and soft performance criteria and so on. Solutions can be interrogated and demonstrated through an interactive virtual environment, in which multi-option scenarios can be evaluated against specific user-defined criteria. Findings have identified several core benefits, including the ability to: justify decisions corroborated with detailed data; evaluate options against each other; interrogate objects at a much greater detail than before; and see the effects of changes in a 'real-time' environment.

Key words: hybrid concrete construction; performance measurement; prototyping; simulation; virtual reality

Introduction

Hybrid concrete construction (HCC) is ostensibly the combination of *in situ* concrete with precast concrete, steelwork or other materials (Goodchild, 2001). It offers users the flexibility to incorporate building elements (such as floors, beams and columns) as *in situ* or precast arrangements (in any combination), thereby facilitating optimal construction performance (Goodchild, 1995; Baiche, 1997). Current research postulates that HCC can satisfy client demands for high quality and low costs, whilst also maintaining safe and rapid methods of construction (Glass and Baiche, 2001; Goodchild, 2001). Many hybrid construction variants have been developed internationally; however, their adoption has been slow in the UK (Glass and Baiche, 2001). This phenomenon is attributed to barriers in the technical and practical aspects, and the availability of appropriate design guidance/information which sets out the advantages of hybrid concrete with respect to such performance criteria eg, quality, time, cost and so on (Goodchild, 2001). It is thus argued that the adoption and use of HCC could offer the UK construction industry considerably greater opportunities if the

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 10.1191/1471417506ci104oa

potential benefits were better communicated to all stakeholders involved in the process. In this context, virtual prototyping techniques could help remove some of these barriers by integrating these diverse issues into a clear and coherent decision-making tool (Sexton *et al*., 2005; Zhang *et al*., 2003).

Hybrid concrete construction

HCC is a technologically advanced approach to frame construction that draws upon a variety of technologies to achieve an optimized solution (Goodchild, 2001; Glass and Baiche, 2001). However, it is often difficult to find an optimized solution because of entrenched adoption barriers. Goodchild (2001) condensed these barriers into three distinct categories:

Engineering skills
HCC requires a sophisticated approach to the design of the overall structure, yet the knowledge and skills of individual professional engineers to assimilate the new production and assembly knowledge are often insufficient.

Designer information
During the design process, designers are not receiving or acting upon the large quantity of basic design information associated with HCC, such as advantages to be gained and tolerance issues involved. This omission therefore often rules out the adoption of HCC.

Measuring performance
The type and range of hybrid solutions available often makes it difficult to measure and assess performance. This can therefore affect the client's decision-making process vis-à-vis selection.

These issues therefore need to be addressed in order to make HCC a more attractive solution. It is also postulated that virtual reality (VR) technology could help remove some of these barriers by integrating these diverse issues into a clearer and more coherent communication and decision-making tool (Zhang *et al*., 2003, 2004).

Virtual reality in construction

The use of VR within the construction industry can offer many benefits to stakeholders (Aouad *et al*., 2000; Bouchlaghem *et al*., 1996; Savioja *et al*., 2003; Kam *et al*., 2003). It can be used for example, to support collaborative visualization and design decisions; help increase productivity; improve team communication; and reduce costs (Brooks, 1999; Campbell, 2000; Egan, 1998; Fernando *et al*., 2001; Hamilton *et al*., 2001; Jones and Webb, 1997; Savioja *et al*., 2003; Shelbourn *et al*., 2001). These advantages are further enhanced where the three-dimensional, sensory immersing environment interactively responds to (and is controlled by) the behaviour of the user (Pimentel and Teixeira, 1995). These have been included into the current themes of how further developments in information technology (IT) could improve the future construction projects undertaken by the Working Commission CIB W78 (IT in Construction). They state these benefits as 'improved communications in all life-cycle phases through visualization' and 'increased opportunities for simulation and what-if analysis' (Amor *et al*., 2002).

There is a growing momentum to actively adopt VR within construction (Aouad *et al*., 2000). For example, Campbell (2000) investigated the use of virtual reality modelling language (VRML) in the production and communication of construction documents; Aouad *et al*., (1997) developed Open Systems for Construction (OSCON) which provides an integration hub for hitherto incompatible software systems; Petric *et al*. (2002) developed a VR-modelling environment to allow users with a physical impairment to participate in the architectural design process; Murray *et al*. (2000) developed FutureHome, a 4D-construction (length + width + height + time) VR-based environment that facilitates the visualization of a building construction sequence according to a given schedule; Fernando *et al*. (2001) developed DIVERCITY, which provides users with a 4D VR simulation model. These developments in VR offer users enhanced levels of interactivity and visualization opportunities, allowing them to make changes and 'simulate' a proposed design solution before construction actually begins.

However, whilst there is growing evidence that VR is continually having an impact on the construction industry, there are still some concerns regarding communication barriers regarding stakeholders from differing backgrounds – especially those lacking Computer-aided design (CAD) experience (VTT, 2005). Furthermore, VR on its own is not a panacea solution for all problems (especially at the conceptual design stage), as it is traditionally difficult to capture and represent qualitative information into three-dimensional representations. In this context, a Virtual Prototyping System is used to explore the nuances of these difficulties using the domain of conceptual design and the context of HCC (to demonstrate the capabilities of a simulation and modelling tool). Here, virtual prototyping is regarded as a digital design approach based on 'simulatable' computer models of a building frame. Virtual prototyping technology is based on integrated application of advanced modelling, multiple discipline simulation, interactive user-interface and virtual reality techniques (Wang, 2002).

Research aim, objectives and research methodology

HyCon is an Engineering and Physical Sciences Research Council (EPSRC) funded collaborative research project. It has 10 industrial partners (see Acknowledgements) and three academic partners (University of Salford, University of Loughborough, and the University of Wolverhampton). The overall project aim was to simulate the performance of concrete structures using virtual prototyping techniques.

The main objectives of the HyCon project were:

- to develop an appropriate methodology to assess the performance of *in situ* and hybrid concrete based on selected criteria (including time, production costing and whole life costing);
- to create a 'proof of concept' model which can be used to assist stakeholders make frame design decisions (eg, *in situ* versus hybrid);
- to identify the technology transfer issues from a cultural (ie, diverse disciplines interacting to deliver a single output) and human (ie, the skills needed to both understand and use such technologies) resources perspective; and
- to test and validate the conceptual model against a 'live' project, supported by domain experts.

From a research methodology perspective, a range of approaches were used, including a comprehensive literature review (to identify 'soft' and 'hard' performance requirements); the use of one detailed case study (to elicit stakeholder needs and performance data, and to simulate the performance of the model against a 'live' project); the undertaking of a software selection process (to determine the most appropriate technological solution); and the process of rapid prototyping (to test simulation approaches prior to full development). The outcome of this research created a simulation modelling tool which can simulate the performance of a building frame in a virtual environment – allowing various stakeholders involved at the early stages of the design process to perform 'what-if' scenarios before important decisions are made; specifically, the choice to commit to a particular type of structure. The findings from the case study verified the predefined criteria as well as the methods used in analysing the performance of different building frame designs. However, it also showed that some aspects were not included in the current prototype, eg, the production time for precast concrete and delivery time. This paper focuses on the design and development aspects of the virtual prototyping system, hereafter known as HyCon.

The HyCon virtual prototyping system

The construction process can typically be divided into three stages, namely: the design stage, the construction stage and the post completion stage. In this context, any decisions made at the design stage will have ramifications on subsequent events ie, on the whole project (Baldwin *et al*., 1998; Idrus and Newman, 2003; Gould, 1997). Using this paradigm, and the context of HCC, it was perceived that the design engineers could be considered as key 'players' in the HCC supply chain (Goodchild, 2001) as they normally predetermine the use of HCC as one of the potential frame solutions. Therefore, the conceived focus stage for the use of the virtual prototyping system was considered to be the design stage – more specifically, the conceptual design stage (as this was the stage where the decision to adopt the frame was typically taken).

The conceptual design stage can be further subdivided into four key stages, specifically: the user needs analysis and performance criteria definition stage; the design alternatives stage; the performance prediction and evaluation stage; and the design solution stage. The main stakeholders associated with the design stage are normally identified as the client and the design professionals, which naturally embraces the architect, engineers and design consultants (Zhang *et al*., 2004) – the details of which can be seen in Figure 1.

The modelling approach adopted for HyCon followed the parameters ascribed by the Integration Definition for Function Modelling (IDEF0) methodology. This enabled detailed system functionality to be modelled for the conceptual design stage. The IDEF0 arrangement for HyCon can be seen in Figure 2.

The functionality of the HyCon model embraces four core issues, ranging from defining the performance criteria (A1), through to the decision making component (A4). This approach was adopted as informed decisions often require careful analysis of significant amounts of information, especially concerning the combination of available options vis-à-vis performance simulation (Papamichael, 1999). Therefore, adequate, timely and 'useful' data are crucial requirements in executing a successful project; and thus vital for the conceptual design stage (Gould, 1997). At this stage, each stakeholder contributes particular knowledge to the project,

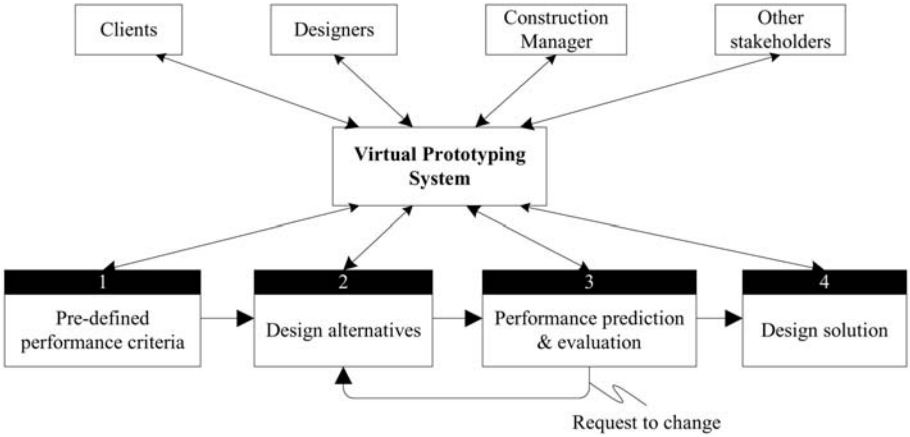

Figure 1 Conceptual relationship: system, stakeholders and process

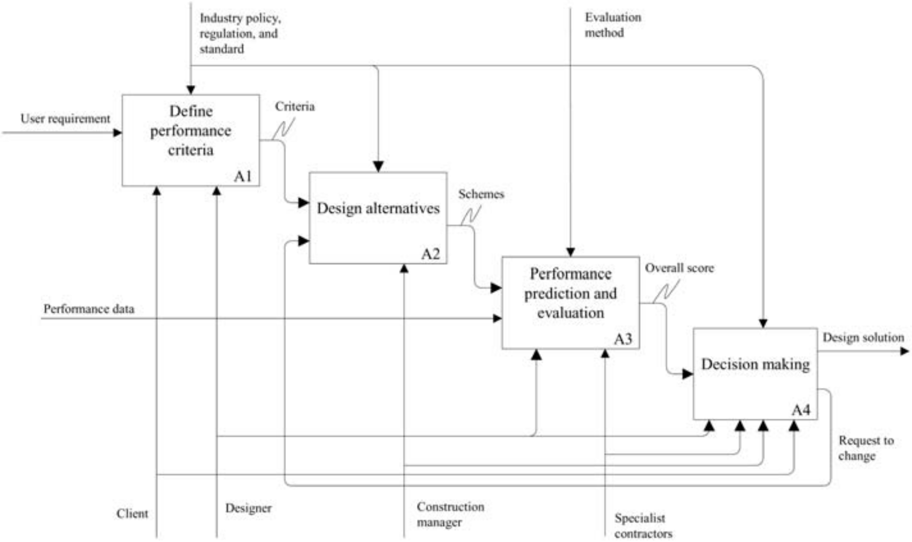

Figure 2 HyCon IDEF0 model

which naturally includes such issues as norms and values, politics and sensitive commercial information. It was therefore important to be able to 'map' these issues into the virtual prototyping system in order to make it sufficiently flexible to accommodate these nuances. From a design perspective, eg, the modelling prototype was developed to provide interactive functions, thereby allowing users to verify and refine the design plans by using different construction alternatives; an example of which might include changing specific building elements such as floors, beams, columns and walls, or altering the material properties form, eg, concrete to steel.

Communication and knowledge sharing is fundamental in supporting collaborative decision-making among all stakeholders during the conceptual design stage (Gould, 1997), and is often hampered by conventional paper-based representation (Liston *et al*., 2001). This was reinforced by Barrett (2001), who identified that high level communication and commitment (underpinned by mutual trust) was essential in the HCC design process. In this context, it was important to accommodate 'rich' media attributes (Pietroforte, 1997), including the ability to visualize design and construction information in three dimensions (3D). This functionality was extended to accommodate photo-realistic images for realism (Hobbs and Dawood, 1999), and extended flexibility in order to support distributed access (Issa, 1999; Caneparo, 2001) and maximize consensus.

From a performance prediction and evaluation perspective, building design decisions are often based on the comparison of design alternatives with respect to a variety of performance considerations. In this context, the HyCon prototype was developed to dynamically predict the cost and performance characteristics of different design proposals – as performance assessment functions are often vital to support the effective design decision-making process (Petric *et al*., 2002). This functionality can increase the design support effectiveness by: 'reducing the number of parametric variations a designer may need to explore; and enhance the users' understanding of the interactions between various design and performance variables for a given partial design solution' (Mahdavi, 1999).

It was also important that project participants could compare the quality of different potential solutions against performance criteria – the functionality of which can provide two-way analysis (Mahdavi, 1999), ie, 1), the user can 'make a change in a design attribute and observe the resulting changes in other design variables when one or more relevant performance variables are constrained. This is a way of examining 'trade-offs' among design attributes for a given set of performance indices'; and 2) the user can 'make a change in a performance variable in order to see the corresponding changes in design variables'. For example, the provision of 'what-if' analysis where different options and scenarios can be simulated, can allow users to interrogate and analyse multi-criteria performance, thereby adding more value to the design decision-making process. As a result, the preferred and most appropriate option can be selected.

Prototype architecture

The development schematic flow of data for the HyCon prototype can be seen in Figure 3. This follows a central database approach (Zhang *et al*., 2003), the framework of which uses the Industry Foundation Classes (IFC) architecture for information interchange and retrieval (IAI, 2005).

Users access all information from the central database using a VR interface. This interface links to the CAD database directly. However, the CAD file must be IFC-compliant, as all data interchange needs to observe IFC 'handshaking' protocol. In this context, the ArchiCAD© CAD package was chosen as the design tool due to its IFC compliance (as data can be imported and exported in IFC 2 × format). This was complemented with a bespoke developed Visual Basic (VB) program built on the IFCsvr ActiveX Component from SECOM (http://www.secom.co.jp/index-e.html). This enabled information to be retrieved from the IFC file and saved in a traditional database eg, Microsoft Access©. Furthermore, as the data stored is predominantly geometric-based; eg, building elements' coordinates, and other forms of data needed to be accommodated; eg, lifecycle cost and time performance data.

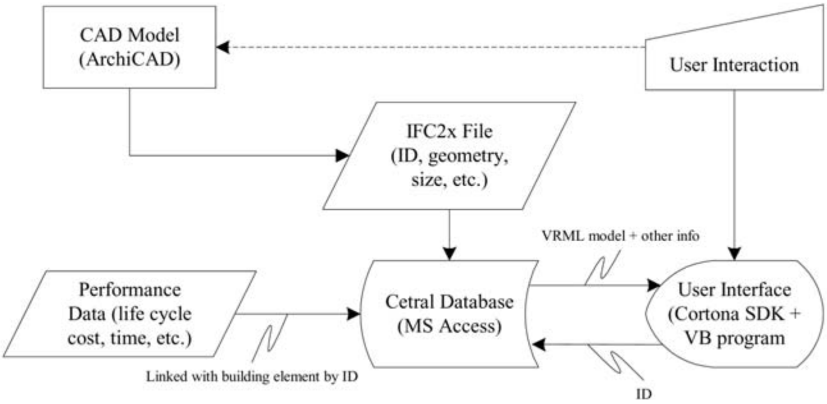

Figure 3 HyCon framework architecture

This information had to be accommodated by linking it using an object ID. The resultant information is then incorporated into a VB-based VRML model for assimilation and manipulation. The VRML chosen for the prototype development was Cortona SDK from Parallel Graphics (http://www.parallelgraphics.com). This was used to create active functions into the prototype system, which facilitated the interactive manipulation of VRML model. Cortona SDK was specifically chosen because it allowed ‘calls’ to an external program environment (ie, Visual Basic) to access and manipulate various objects within the VRML environment.

Performance criteria

An important aspect of any modelling tool is its ability to assess solutions based on predefined performance criteria. In the context of the HyCon project, this criteria was divided into two categories, specifically: ‘hard’ and ‘soft’ performance criteria (Oloke *et al*., 2003; Soetanto *et al*., 2004). A ‘hard’ performance criterion is predominantly quantitative by nature, and is therefore tangible; eg, production time and cost; whilst the ‘soft’ performance criterion is essentially qualitative and intangible; for example, physical appearance, sustainability and satisfaction level. From a performance perspective, Goodchild (1995) highlighted that cost was considered as one of the most influential factors in the choice of frame material. However, whilst it can be argued that the predominant decision drivers are still ostensibly tangible eg, time and cost (as these are the two issues that stakeholders continually consider most important), it was also considered necessary to address the ‘softer’ issues in order to holistically evaluate hybrid concrete against other options using a multi-criteria approach (ie, ‘hard’ and ‘soft’ data). The incorporation of both ‘hard’ and ‘soft’ performance criteria was also adopted to address the findings of Barrett and Aouad (1999) regarding the use of ‘soft’ criteria when assessing the appropriateness of construction frames. In the prototype, two ‘hard’ criteria (time and cost) and 31 ‘soft’ criteria in seven categories were chosen

(Soetanto *et al.*, 2004), specifically: 1) physical form and space; 2) construction process; 3) long-time sustainability; 4) establishing confidence; 5) building impact; 6) physical appearance; and 7) client satisfaction.

HyCon interface and functionality

The HyCon prototype is based on Scheme 1 of a typical M62C3 building: a three-storey concrete building with hollow core slabs and post-tensioned *in situ* beams on *in situ* columns (Goodchild, 2001). This option was chosen as it is typically more representative of existing hybrid concrete construction (Goodchild, 2001) and is thus better able to engage with and elicit feedback from industry.

HyCon has three main functions, specifically: query, edit and site simulation. The query function allows users to query attributes of each single building element; eg, material, size, cost and time; the edit function allows users to change the attribute (material) of building elements and accordingly the cost and time of the scheme will be changed; and the simulation function allows users to see how the building will look like after the data has been input. Within these three core functions, users are able to edit data and see the effects of changes made. For example, if users change the material of some building elements, the tool will automatically calculate the new cost and time of the scheme and show the results on screen in comparison to the former scheme. The soft criteria can be adjusted to suit individual preferences – the specifics of which enable the outcomes to be evaluated and tailored to suit the desired needs. Furthermore, the soft criteria can be customized (ie, items can be added or deleted as appropriate), including the weightings (see Figure 4). This flexibility enables the end users to feel more engaged with the design choices made, as they can calculate the final score of each design alternative with regard to the specific criteria and weightings specified.

The history function of the HyCon tool enables users to evaluate options and save the changes accordingly. This function concatenates changes sequentially, thereby creating a physical archive of amendments made, thereby enabling key decisions to be 'captured' in the database at important points for subsequent discussion and evaluation by the design team. In this context, it also allows users to reflect back in date order to see what was changed, and how this change had an impact on the scheme's outcome. These details can also be supplemented with personal notes and comments to help other users appreciate the rationale behind the thought process at the time these changes were made, thereby acting as a legacy archive. The history function option can be seen in Figure 5.

The HyCon tool was designed with high levels of interactivity in mind. In this context, an easy to understand and navigate user interface was considered one of the most important features. HyCon therefore incorporates several intuitive pull-down menus and help options, supplemented by navigation and quick access buttons (see Figure 6). This additional functionality enables the VR environment to be navigated and interrogated easily. For example, users can 'walkthrough' the frame using the mouse and be able to see all the interconnecting members. They can also click the mouse button on any of the components to determine composition, attributes and so on. Furthermore, the functionality is flexible enough to allow changes within this environment eg, if one of the columns was selected, this could be changed to steel eg, the interface would then give the user the opportunity to make this change local (ie, just this one column), or global (all of the columns). The resulting

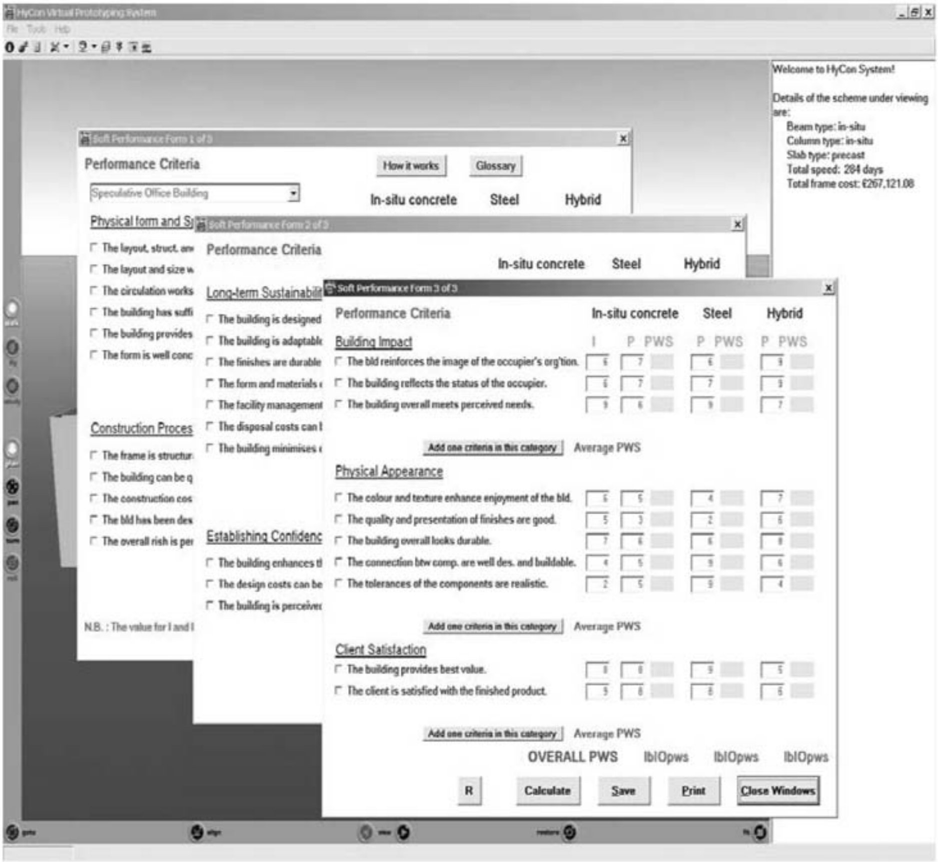

Figure 4 Soft criteria and weighted options

changes can then be seen immediately on the screen, along with the corresponding effect on time and cost.

Another function deemed important to include in the HyCon model was an ability to anticipate what finishes could be achieved (as very often users are unable to appreciate texture, colour and so on in a simulated environment. In this context, photographic representations were included to portray anticipated outcomes of design alternatives (see Figure 7). This function can also be customized by end-users, thereby allowing them to add bespoke images of their choice as required.

HyCon evaluation

The evaluation process of this prototype tool was achieved with construction industry participation, supported by domain experts from the software industry and academia. Firstly, an industry workshop was held to test the alpha prototype. Six industrial representatives

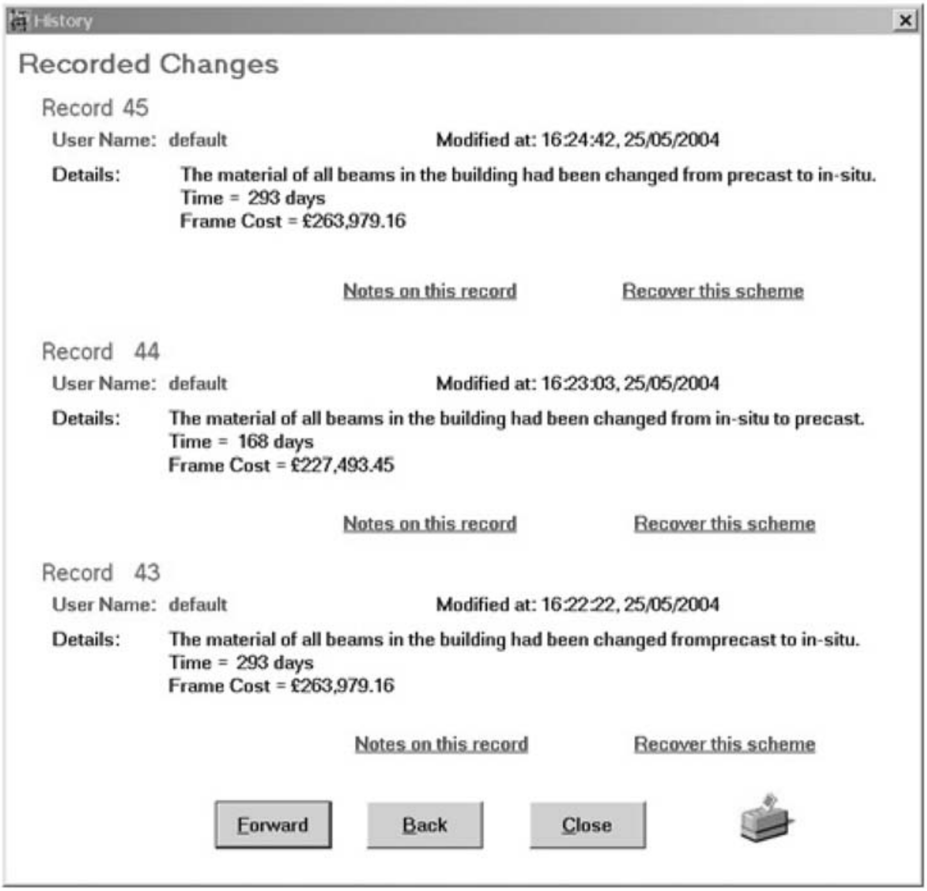

Figure 5 The history function

(covering the professional institute, designer and specialist subcontractors' perspective) contributed to this process. Feedback was analysed for the beta prototype stage of development. This was followed by a series of 'road shows', where this tool was brought to industry partners for interaction and validation. The feedback from this stage was analysed for the final stage of prototype development. The evaluation process was undertaken not only to achieve accuracy and robustness of the model itself (including data validity), but also to validate 'appropriateness of fit' vis-à-vis meeting industry expectations. In general, the tool was considered useful for HCC to be adopted during the design stage. This feedback represents a significant step forwards towards the more objective decision-making process in selecting an appropriate structural frame; and subsequently could offer commercial advantages for end-users. However, the participants also pointed out some aspects where the prototype could be improved, eg, building foundation issues needed to be considered in more detail. This is an area for future research and development.

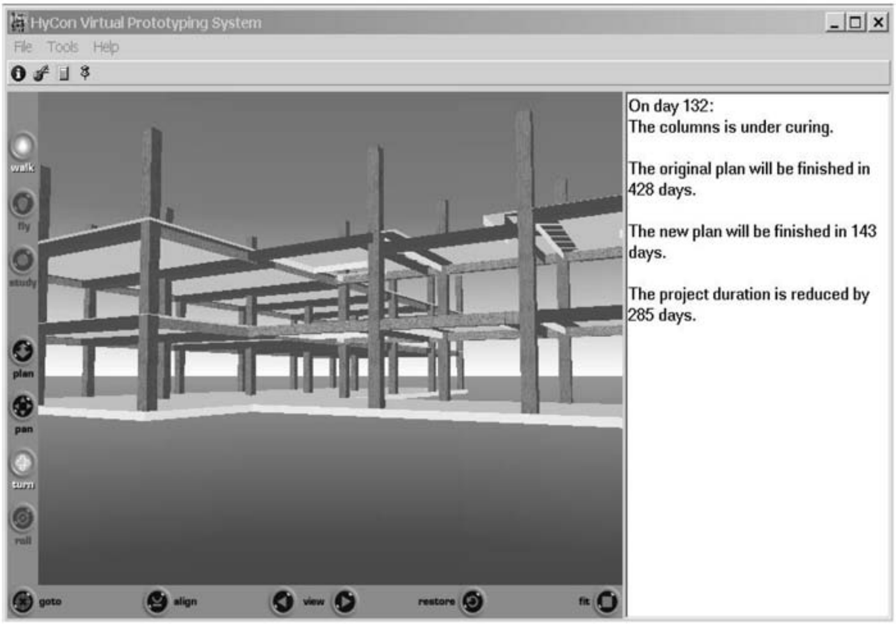

Figure 6 The HyCon simulation interface

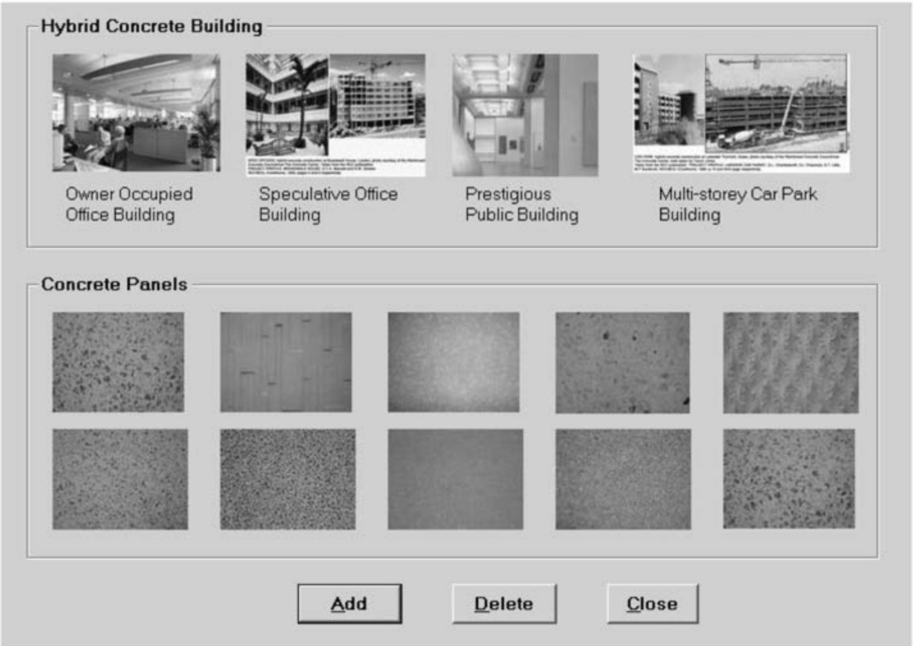

Figure 7 Photographic representation archive

Conclusion

There is a growing belief within the concrete frame fraternity that HCC could answer client demands for higher quality, lower costs, and faster construction. However, there are several barriers associated with the wider adoption of hybrid concrete in the construction industry which need to be formally addressed in order to improve industry uptake. This paper presented the HyCon tool as a way forward, which demonstrated how this virtual prototyping tool could overcome some of these barriers in order to facilitate wider adoption.

This prototype was specifically designed for the conceptual design stage of the construction process, and offers users enhanced decision-making opportunities within a simulated VR environment. More importantly, it can facilitate the communication and knowledge sharing process among stakeholders. This flexibility is particularly innovative, in that it allows scenario modelling through 'what if' analysis, supported by a knowledge management capability to compare previous utilised scenarios with current practice. Furthermore, it allows real time access to productivity drivers (time, cost and whole life costing) which users can input directly (and continually revise as appropriate), thereby supporting continuous improvement. This tool also allows different design alternatives to be archived, along with note-taking functionality to record design decision rationales, for future interrogation, adaptation and reuse. In this context, users are able to make more objective and informed decisions, rather than decisions based on unreflecting preconceived ideas of 'standard' structural frame solutions regardless of end-users' unique needs or characteristics of a particular building.

Whilst this HyCon tool is a major step forward in the conceptual design process associated with HCC and the decision making process, there are however three caveats that need to be raised: 1) that the industry as a whole needs to encourage tools of this nature to pervade the decision-making process; 2) that industry adopt IFCs in order to improve the standardization of data interchange; and 3) that the HyCon prototype is only able to model data that has been entered or imported (and is therefore only as accurate as the data entered).

Acknowledgements

This project was funded by the EPSRC, and this support is gratefully acknowledged.

The academic team consisted of: the University of Salford, UK (project leader); Loughborough University, UK; and the University of Wolverhampton, UK. The 10 collaborating firms were: ABC Structures; the British Precast Concrete Federation; Computer Sciences Corporation; Curtins Consulting Engineers; the Concrete Centre (formerly Reinforced Concrete Council); Edmund Nuttall; HBG Construction; Interserve Plc; Trent Precast Concrete Ltd; and Whitby Bird and Partners.

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